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# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



### THESIS

**A HEURISTIC FOR LAND-ATTACK PREDESIGNATION**

by

Bertram C. Hodge

December 1999

Thesis Advisor:

Alexandra M. Newman

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**A HEURISTIC FOR LAND-ATTACK PREDESIGNATION**

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B.S., Purdue University, 1993

Submitted in partial fulfillment of the  
requirements for the degree of

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## ABSTRACT

Predesignation is the assignment of land-attack missiles on surface ships and submarines to target aim points. The assignment process has two stages: (1) the allocation of land-attack missiles to launch platforms, considering all tasks and platforms simultaneously; and (2) given this preliminary allocation, the refined assignment of land-attack missiles to tasks aboard an individual platform, separately considering each platform and the associated allocations obtained from (1). This thesis addresses only the *first stage*, i.e., the automated allocation of land-attack missiles to surface ships. Currently, strike planners possess no tools that yield consistent and reproducible assignments. Two previous NPS models address the allocation of tasks to launch platforms. One does not address details such as multiple launch areas or multiple time periods, and the other proposes a model that is too computationally expensive to implement in an operational setting. In this thesis we develop a tool to yield allocations similar to those obtained with the latter model in a much shorter amount of time.

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## **THESIS DISCLAIMER**

The reader is cautioned that the computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

The Java procedure developed for this research is available from the author or his advisors, but should be requested via Naval Surface Warfare Center, Dahlgren Division, VA.

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## LIST OF TERMS AND ABBREVIATIONS

National Command Authority (NCA)	The members of the executive branch of the government that grant authorization to use ship-based land-attack missiles against specified targets.
Commander In Chief (CINC)	The officer in command of a theater of operations.
Tomahawk Strike Coordinator (TSC)	The officer on a Battle Group or Naval Component Commander staff responsible for the employment of sea-based land-attack missiles.
Naval Surface Warfare Center Dahlgren Division (NSWCDD)	A naval command that conducts research on weapons system development and use.
Tomahawk Land-Attack Missile (TLAM)	A sea-based cruise missile capable of striking targets ashore.
Block	The generation of a Tomahawk missile. An older block-II Tomahawk has a standard engine type and guidance system. The newer and more expensive block-III has an enhanced engine and advanced guidance system in addition to the original block-II guidance system.
Tactical Tomahawk	A planned future version of the Tomahawk missile with improved range and reduced preparation time.
Land-Attack Standard Missile (LASM)	A planned future land-attack missile based on the Standard Missile.
Task	A pre-planned mission required by a ship to prepare a missile for launch against a specified target ashore. A task is defined by its primary task part and may have ready-spare and/or back-up task parts for redundancy.

Missile Mission Matching List  
(M<sup>3</sup> List)

A prioritized list of missile types that can perform a given task. The prioritization is ordered with respect to ascending missile capability. The first missile on the M<sup>3</sup> list for a task is the least capable missile that can perform the mission. To maintain the greatest capability for follow-on tasking, the least capable missile is preferred.

Primary Task Part

A pre-planned mission required by a ship to prepare a missile for launch against a specified target ashore. Primary task part information includes a M<sup>3</sup> list, target, and weapon launch time. Ships assigned primary task parts may execute them without further authorization.

Ready-spare Task Part

A task part that provides redundancy for an associated primary task part. Ready-spare task parts have the same characteristics as the primary task part, such as the M<sup>3</sup> list, and must be assigned to the same ship that holds the primary task part assignment. Ships assigned ready-spare task parts may execute them if the corresponding primary task part fails to transition to cruise mode.

Back-up Task Part

A task part that provides redundancy for an associated primary task part. Back-up task parts have the same characteristics as the primary task part, such as the M<sup>3</sup> list, and must be assigned to a ship other than the ship with the associated primary task part. Ships assigned back-up task parts must be specifically directed to execute back-up task parts.

Vertical Launch System  
(VLS)

The storage, preparation, and launching system for several types of weapons, including Tomahawk missiles.

## Half-module

A component of the Vertical Launch System composed of four individual cells; each cell provides storage and launch preparation for a missile. Depending on the missile types within a half-module, power requirements may restrict the half-module to prepare only one missile at a time.

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## EXECUTIVE SUMMARY

Assigning land-attack missiles aboard ships and submarines to target sites is becoming increasingly complex because of the development of new missile types, the construction of additional land-attack-capable ships, and larger per-ship missile capacities. No tool currently exists to assist planners with quick, systematic and reproducible target-to-ship assignments when considering multiple ships and multiple time periods-simultaneously. Naval Postgraduate School student LT Brian Kirk (USN) has developed an optimization model for preliminarily assigning aim points to surface ships. It possesses multiple objective functions to capture the following goals, in order of priority: (i) minimize unmet tasking, (ii) minimize the use of ships performing other critical activities, (iii) use as many missiles as possible from designated ships, (iv) distribute the tasking as much as possible among the remaining employed ships, (v) minimize the use of ships from remote geographic areas, (vi) use the most desirable missile type (e.g., the least capable missile) possible, and (vii) maximize residual firing capability. Generally speaking, the model imposes the following restrictions: (a) adherence to doctrine governing the use of missiles, (b) allocation of missiles to specially designated ships, and (c) launcher missile preparation restrictions.

Although Kirk's model provides sound solutions, and the best software available is carefully tuned to maximize responsiveness, the solution times are too long for the model to be used in an operational setting. In this thesis, we develop a faster, heuristic procedure based on Kirk's model that provides comparable solutions for most goals.

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## I. INTRODUCTION

### A. BACKGROUND

Predesignation is the assignment of land-attack missiles aboard ships and submarines to target aim points. The assignment process has two stages: (1) the allocation of land-attack missiles to ships, considering all tasks and ships simultaneously; and (2) given this preliminary allocation, the refined assignment of land-attack missiles to tasks aboard an individual ship, separately considering each ship and the associated allocations obtained from (1) [Fennemore, 1999a]. The scope of this thesis is limited to the *first stage* assignment of land-attack missiles aboard surface ships to aim points. US National Command Authority (NCA) authorizes a regional Commander-in-Chief (CINC) to use ship-based land-attack missiles for specified targets. The CINC passes these aim points down the chain of command to the Tomahawk Strike Coordinator (TSC) for ship assignment.

Predesignation requires NCA and CINC to provide the following inputs to TSCs: a list of target aim points, required and feasible missile types for each aim point, the missile quantity to be used on the aim point, missile time-on-target, and missile assignment redundancy required. TSCs prepare a list of pre-planned missions based on this input. These pre-planned missions, referred to hereafter as *tasks*, dictate the launch area and are compiled to form a single target list. Tasks on the target list are matched to available firing ships.

An automated assignment system would allow predictable planning times, and consistent, reproducible task-to-ship allocations. That is, given a set of inputs, the automated system would always yield the same first-stage allocations. Strike planners today have no written guidance or automated tools to help them determine which ships should participate in a strike and how tasks should be assigned to the participating ships. Because assignments are based on operator experience, planning times vary from staff to staff. Different staffs can be expected to produce differing results. Even a single staff would likely produce a different assignment given the same inputs at different times.

Strike warfare is growing in importance and complexity for the United States surface navy. Land attack is currently focused on striking fixed strategic targets in campaigns or single engagements. Future requirements expand the role of strike warfare to include infantry close support and the attack of mobile targets. Future ships can be anticipated to accommodate a larger number of missiles, greatly increasing missile selection choices. New missiles will enable the Navy to strike farther into enemy territories, attack a wider spectrum of target types and execute strikes more quickly. A demand for faster strike planning will surely accompany these new capabilities. TSCs will be poorly served by intuition alone in this more complex environment.

Currently, the Tomahawk Land-Attack Missile (TLAM) is the sole land-attack missile and is distinguished by its generation. An older block-II has a standard engine type and guidance system. The newer and more expensive block-III has an enhanced engine and an advanced guidance system in addition to the original block-II guidance

system. The more capable block-III can always be substituted for tasks requiring a block-II missile, but the reverse is not true.

A task specifies, among other things, capable missile types, warhead and block type. Some tasks possess several feasible missile types. This prioritized list of missiles is called the mission missile matching ( $M^3$ ) list. If possible, it is desirable to select the most preferable missile on the  $M^3$  list. Tasks may have up to three parts.

*Primary task parts* are missions assigned to a ship for execution at the specified launch time. No other authorization is needed to launch a missile. All other task parts provide redundancy for primary task parts.

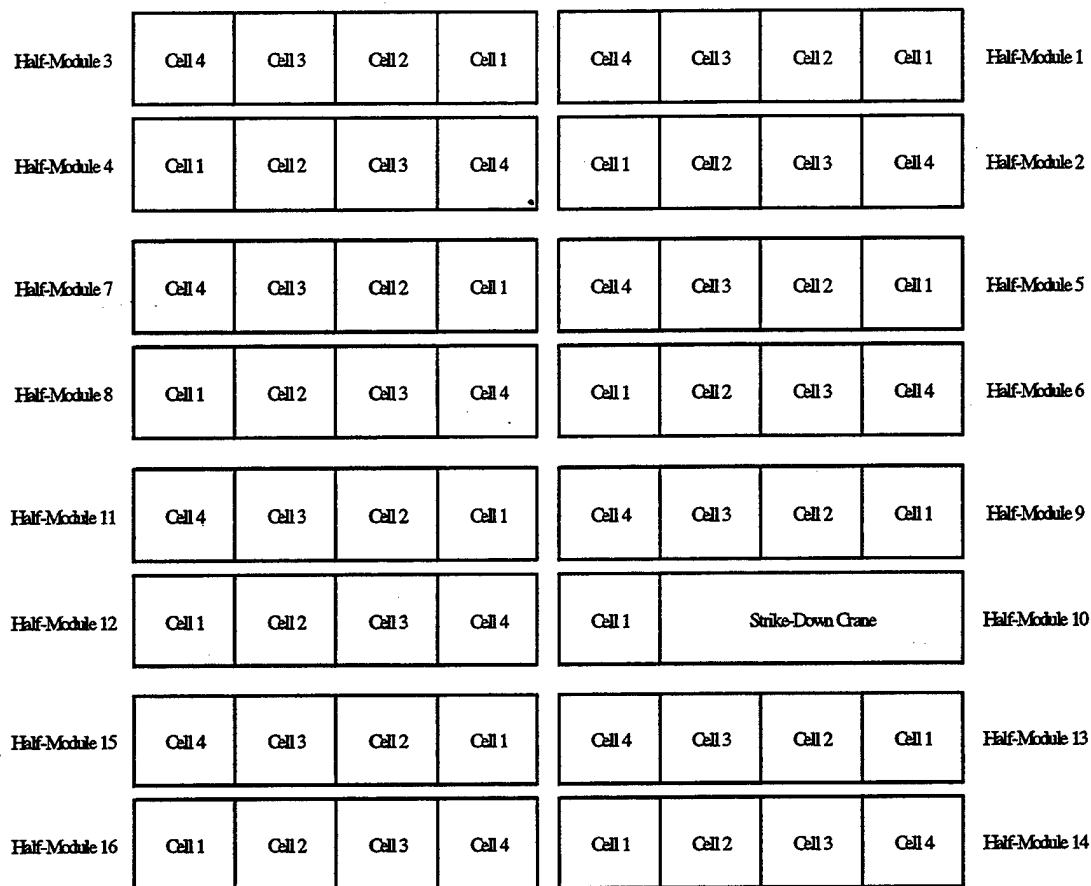
*Ready-spare task parts* are assignments associated with a primary task part on the same ship. Ready-spare task parts authorize a ship to prepare a missile to launch only in the case that the associated primary missile fails to transition to cruise mode.

*Back-up task parts* are assignments associated with a primary task on a different ship. The assignment of back-up task parts to a ship authorizes it to prepare a missile for launch if the associated primary missile fails to transition to cruise mode.

*Ghost missions* are redundant tasks that may support more than one primary task part. A ghost task is not restricted to be assigned to the same ship as the primary task part. Ghost missions take advantage of a missile's ability to have its flight path rapidly reprogrammed. Once the TSC directs a ship to fire a ghost task in support of a primary task, the missile is no longer available to support any other primary tasks.

Tasks also have a limited geographic area from which they must be executed. Ships that are in the appropriate area and are capable of executing the task are known as *geo-feasible* ships.

TLAMs aboard surface ships are housed, prepared, and launched from a vertical launching system (VLS). A VLS is composed of a series of half-modules with four cells each. Each cell may contain a single land-attack missile. Due to power consumption during TLAM preparation, only one missile per half-module may be prepared for launch at any given time [Fennemore, 1999b]. Some VLSs possess a strike-down crane in place of three cells for ordnance handling. Figure 1 displays a VLS with a strike-down crane.



**Figure 1: Surface Ship Vertical Launching System (VLS).** This VLS has 16 half-modules for the storage and preparation of missiles. The strike-down crane spans three cell allowing for a maximum loadout of 61 missiles.

Ships fire land-attack missiles at targets ashore during multiple *time periods*.

Time periods are denoted by intervals of clock time, and TLAM missiles that are prepared and launched in overlapping time periods may not be allocated to the same half module. A *strike* is an attack consisting of one or more time periods.

The number of missiles of a particular type that can be launched in a single time period is the strike capability, or *salvo size*. Salvo size is limited by half-module power constraints imposed on missile firing capability during overlapping time periods within a strike.

Missile masking is a negative effect caused by half-module power constraints. Missile masking can occur when a task that requires a missile of a more common type (e.g., TLAM C) is allocated to a half-module additionally containing a rarer missile type (e.g., TLAM D). If a TLAM D missile is required, this allocation could lead to insufficient half-module availability to meet rare missile type tasking even if there are sufficient missiles available. Allocating missiles to tasks requiring the rarer missile types before those requiring the more common types helps reduce missile masking.

## **B. PAST WORK**

Naval Surface Warfare Center Dahlgren Division (NSWCDD) has developed integer programming models to perform single ship (i.e., surface ship and submarine) second-stage predesignation for Tomahawk missiles [Naval Surface Warfare Center Dahlgren Division 1997, 1999]. Naval Postgraduate School (NPS) graduate LT Scott Kuykendall (USN) developed an alternate single time period, second-stage predesignation scheme using a mixed integer formulation [Kuykendall 1998]. NPS graduate LT Brian Kirk (USN) developed a first-stage predesignation formulation for task-to-surface ship assignment of Tomahawk missiles on a theater-wide scale [Kirk, 1999]. His work investigated three approaches: (1) integer programming with a single weighted objective function, (2) integer programming using multiple objective functions and employing a Hierarchical Restriction solution technique, and (3) integer programming using multiple objective functions and employing a Heuristic Hierarchical Restriction solution technique. The weighted objective function method was unable to make allocations with realistically large task sets due to computational intractability and

excessively long solve times. The integer programming methods using Hierarchical Restriction and Heuristic Hierarchical Restriction provide sensible solutions; however, the execution times are too long for the models to be used in a real-time setting.

Kirk formalizes TSC priorities in the assignment of tasks to surface ships as follows:

- Meet all assigned tasking. Kirk assigns a penalty to each task that cannot be assigned.

- Minimize interrupting ships from other duties they may be engaged in. Ships perform a variety of activities while at sea in addition to land attack, e.g., air defense or maritime interdiction. Using ships for strike may prevent or hinder a ship from carrying out these other activities. Kirk applies an employment penalty for using ships engaged in other critical activities.

- Spread primary tasks to as many ships as possible. This is desirable to minimize single points of failure among primary missiles. Kirk uses a binary switch to activate this option in each launch area.

- Spread back-up tasks to as many ships as possible. This is desirable to minimize single points of failure among back-up missiles. Kirk uses a binary switch to activate this option in each launch area.

- Minimize the use of ships from distant areas. Calling a ship into a region for strike incurs a fuel cost, requires transit time, and prevents it from performing other duties. It is important to use all available ships in the most effective manner. Kirk

assigns to each ship a geographic penalty that increases with its distance from a launch area.

-Use as many missiles as possible from designated firing units. When tasks are executed, the participants may be in different stages of their overseas deployments. It is desirable to shoot as many missiles as possible from a ship leaving the launch area shortly after the strike. This allows ships remaining in the area to conserve their missiles for later attacks. Kirk labels such a ship an *expend-ship* and rewards the assignment of missiles to this ship.

-Distribute missile assignment as much as possible among designated *spread* (i.e., non-expend) ships. Spreading task assignment helps ships deplete their missile inventories synchronously. Uneven inventory between ships limits the overall battlegroup maximum follow-on attack capability. Kirk assigns relative penalties for the assignment of missiles to ships according to the ship's deviation of inventory from the battle group average following the strike.

-If possible, use the most preferred missile on the  $M^3$  list for tasking. Kirk assesses a penalty for use of over-endowed missiles.

-Maximize follow-on salvo size. Each ship has a maximum firing capability per strike due to launcher constraints. Task-to-missile assignment should result in a maximum number of missiles capable of being fired in a later strike. Kirk's formulation rewards larger follow-on salvo sizes for each missile type. Each missile type may have an associated weight. The maximum follow-on salvo size for a missile type is the



product of the sum of all half-modules containing a given missile type (disregarding a missile that has been selected for a primary task) and the missile type's relative weight.

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## II. MODELING APPROACHES

### A. PROBLEM DEFINITION

The scope of this thesis is to develop a heuristic to assign tasks to surface ships in a way that will produce results that closely match solutions obtained with Kirk's integer programming formulation. The main benefit of the heuristic is that it will yield solutions quickly enough to be used in an operational setting. Like Kirk's work, the heuristic will account for multiple battle groups, multiple launch areas, multiple time periods and current TSC tasking priorities.

### B. ALGORITHM ASSUMPTIONS AND DEFINITIONS

We make the following assumptions regarding operational procedures, and define several parameters and terms relevant to the execution of the algorithm.

Our model addresses only the *first stage* of predesignation. However, to ensure that task-to-ship assignments are feasible, allocations are made down to the cell level. The cell level assignments could theoretically be used as *second-stage* predesignation allocations, but our cell assignments do not take into account individual ship level details such as assigning tasks to missiles in order of their maintenance due dates.

Cells are capable of having tasks assigned to them if they have the correct missile type and do not already have a task assigned to them. Half-modules are capable of having a specific task assigned if they have a cell with the correct missile type and no other task has been assigned to a cell in that half-module that conflicts with the task to be assigned. A ship is capable if it has a capable half-module and is in the task's launch area. Ships that are in a task's launch area are considered to be *geo-feasible* for that task.

Accounting for multiple battle groups in geographically distinct launch areas assumes that task redundancy is handled within each launch area. Ships in battle groups located in one launch area will not provide task redundancy for ships in battle groups located in a different launch area.

In accordance with Kirk's work, each ship has two penalties associated with designating it for tasking: a geographic penalty (*geoPen*) and an employment penalty (*empPen*). Both penalties are expressed in the same arbitrary units. If used in a strike, a ship's total penalty score is the sum of *geoPen* and *empPen*. When this sum is divided by the number of land-attack-capable half-modules available on a ship, the result, denoted *P*, is a relative measure of a given ship's cost for use.

Conflicts among tasks that are to be executed in multiple time periods within the same strike are accounted for by ensuring that power restrictions per half-module are not violated. Any two tasks that have an overlapping missile preparation and launch time are said to *conflict* with each other.

Each task is defined by its primary task part. Ready-spare task parts must be assigned to the ship with the associated primary task part. Back-up task parts must be allocated to a ship other than that containing the associated primary task part. Primary tasks that have associated ready-spare or back-up parts will not be allocated unless all parts can be allocated. It is assumed that ready-spare and back-up task parts have the same  $M^3$  list as the associated primary task part.

The calculation of maximum follow-on salvo size for each ship is made after each strike. Each missile type has a relative weight based on missile capability. Maximum

follow-on salvo size for each missile type is the sum of the number of half-modules that contain a specified missile type multiplied by the relative weight of the specified missile type. The optimistic assumption is made that all missiles assigned to primary tasks will be fired and that ready-spare, back-up and ghost-assigned missiles will not be fired.

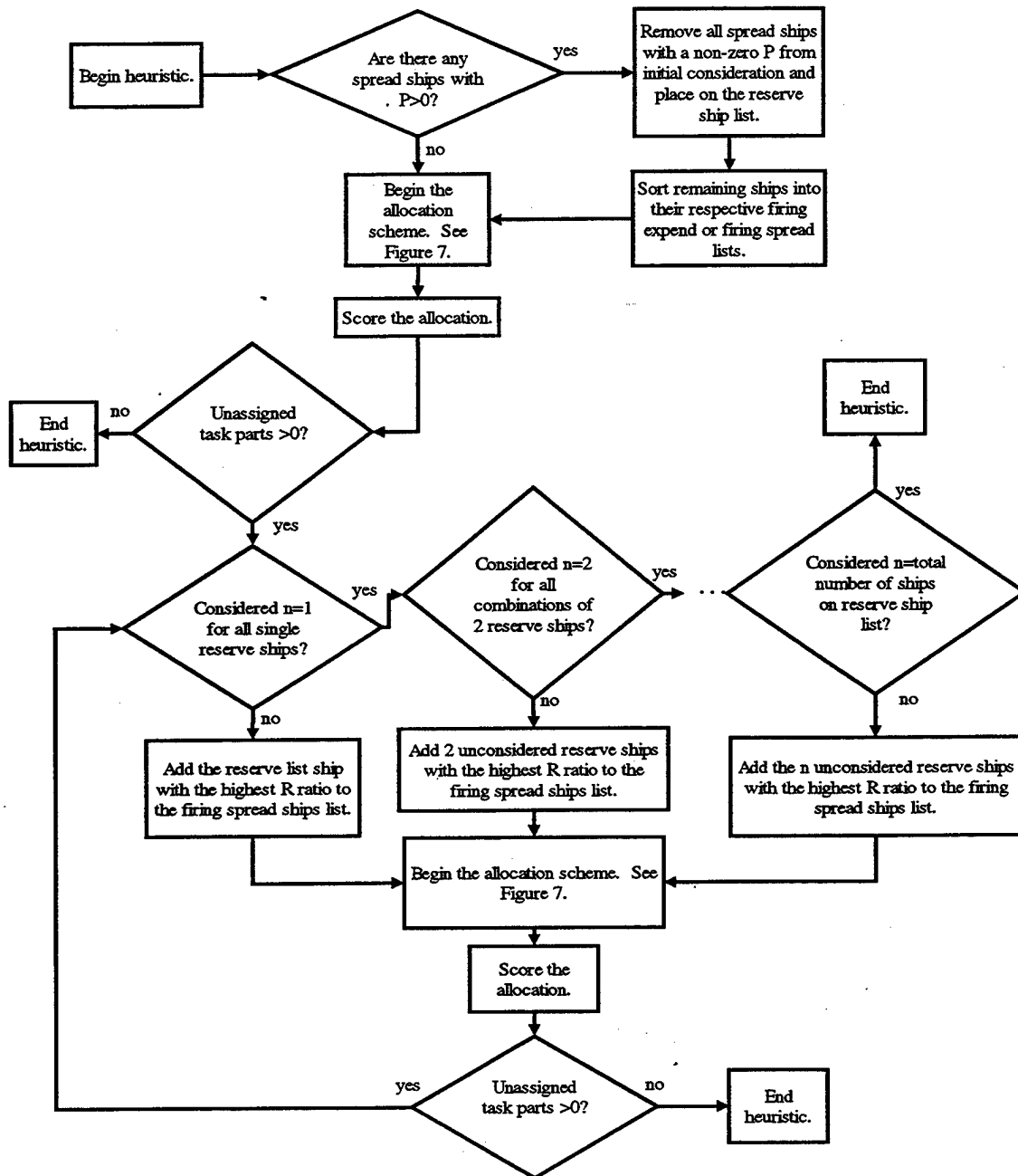
Despite this assumption, missiles allocated to ready-spare, back-up or ghost missions cannot be allocated to another task in a subsequent time period *within the same strike*.

After the strike, the follow-on salvo size can be adjusted to account for any ready-spare, back-up or ghost missiles that were fired.

### C. MODEL PRESENTATION

We now discuss the algorithm in detail. In order to assign tasks to ships, an initial list of candidate ships is needed. This *eligible units list* contains only ships that are capable of land attack. If a ship is selected for use in a strike, it is moved from the eligible units list and placed on the *firing units list*. The firing units list is subdivided into a *firing spread-ships* list and the *firing expend-ships* list based on the respective designation of the ships on the list. An initial set of ships composed of eligible expend-ships, and spread-ships with a  $P$  value of zero are always immediately placed on their respective firing units list. Spread-ships with a non-zero  $P$  value are placed on a *reserve list* and used only if the ships already on the firing units list are unable to accommodate all tasks. If all tasks are assigned (according to the scheme we describe below), the allocations are scored and the procedure ends. If there are unassigned tasks, the model adds to the firing units list the reserve spread-ship with the largest ratio of salvo size to  $P$ , denoted  $R$ , and the allocation scheme is rerun. If all tasks are assigned, the allocations

are scored and the heuristic terminates. If some tasks are not assigned, the ships on the reserve list are considered one at a time in descending order of their  $R$  values in conjunction with the ships on the original firing units list. As soon as a group of ships is identified that can meet all tasking, the allocations are scored and the procedure terminates. If no single ship added from the reserve spread-ship list (combined with the ships from the original firing units list) is able to produce an allocation without unassigned tasks, then two ships with the highest combined  $R$  ratio are added to the firing spread-ship list and the model is run. If allocations still cannot be made for all tasks, all combinations of two ships are added (in descending order of combined  $R$  ratio) to the original firing units list and the heuristic is executed. This method continues, examining the addition to the original firing units list of all combinations of the best  $n$  ships ( $n = 1, 2, \dots$  the number of units on the reserve ship list). The algorithm terminates when either an allocation is made for all tasks, or all reserve spread-ships have been added to the model. Figure 2 illustrates the selection of the initial firing units and the reserve ships.



**Figure 2: Selection of Ships.** The allocation scheme first attempts to make assignments with expend-ships, and spread-ships with  $P=0$ . If this allocation results in unassigned tasks, then reserve spread-ships are selected until either all tasks are allocated or until all reserve ships are added to the firing units list. See Figure 7 for an expanded view of the allocation scheme that will subsequently be discussed.

Cell selection is a sufficient condition to guarantee feasible task-to-ship assignments. For this reason, we make cell assignments to ensure feasibility of our task-to-ship allocation. However, our heuristic does not consider all elements required for second-stage predesignation. Therefore, although these task-to-cell assignments could theoretically be used as the second-stage predesignation allocation, a previously developed model is actually used (see [NSWCDD/TR-95/119 TOMAHAWK Predesignation, June 1995] and [NSWCDD/TR-97/18 Advanced TOMAHAWK Weapons Control System Predesignation, February 1997] referenced in Section 1B) to make the final (second-stage) task-to-cell allocations.

Task-to-cell allocations can be constrained for various reasons. To account for tasks that may be restricted in their task-to-cell assignment, the allocation scheme begins by ordering all tasks by their individual (potentially constraining) characteristics. Tasks that can only be executed by a subset of the ships on the firing units list must be allocated first to increase the chances of a feasible task-to-cell assignment. The number of task parts for each task is given second priority in task allocation. Tasks that require primary, ready-spare and back-up assignments are more difficult to assign than tasks that only require primary and ready-spare assignments or primary and back-up assignments, and are ordered first. Furthermore, we arbitrarily choose to order tasks that require primary and back-up assignments before tasks that require primary and ready-spare assignments. Tasks that require only primary assignments are the least restrictive to assign and are ordered last. The third level of task ordering is based on missile rarity. To minimize missile masking, tasks that require the most rare missiles are assigned before tasks



requiring missile types that are more prevalent. The final level of task ordering is based on the number of conflicting tasks. Tasks that conflict with many other tasks will be more difficult to assign than tasks with no conflicts. Therefore, tasks are placed in decreasing order of the number of conflicts they have.

For example, consider the following unordered task list given in Table 1. Tasks 1, 3, 4 and 5 can only be executed by a single ship and must be allocated before Task 2. Because Tasks 3, 4 and 5 require primary, ready-spares and back-up missile assignments and are more difficult to allocate, they are ordered before Task 1. Tasks 3, and 4 can only be accomplished if assigned to one of four missiles from ships on the firing units list. To minimize missile masking, Tasks 3, and 4 are ordered before Task 5. Finally, Task 3's 23 conflicting tasks make it more difficult to assign than Task 4's 12. Task 3 is ordered first because of this. Table 2 gives the ordered allocation of these tasks.

Task	GeoFe Ships	Task Parts	Missile Count	Conflicts
1	1	1	4	23
2	3	3	5	23
3	1	3	4	23
4	1	3	4	12
5	1	3	10	4

**Table 1: Unordered Task List.** The first column denotes the task number. The second column indicates the number of geographically feasible ships that can execute the task. The third column shows the number of task parts. The fourth column indicates the total number of missiles aboard the eligible ships that can perform this task. The last column gives the number of conflicting tasks.

Task	GeoFe Ships	Task Parts	Missile Count	Conflicts
3	1	3	4	23
4	1	3	4	12
5	1	3	10	4
1	1	1	4	23
2	3	3	5	23

**Table 2: Ordered Task List.** Tasks 1, 3, 4, and 5 can only be executed by a single ship and must be allocated before Task 2. Because Tasks 3, 4 and 5 require primary, ready-spare and back-up missile assignments and are more difficult to allocate, they are ordered before Task 1. Tasks 3 and 4 can only be accomplished if assigned to one of four missiles. To minimize missile masking, these tasks are ordered before Task 5. Task 3's 23 conflicting tasks make it more difficult to allocate than Task 4's 12. Task 3 is ordered first because of this.

Once tasks have been ordered, they are assigned. For each ordered task, starting with the first, an attempt is made to allocate the task's primary and, if applicable, ready-spare parts to a capable firing expend-ship. If there is more than one capable firing expend-ship, we use a *half-module scoring method* to determine which ship to use for the task. Using this method, each firing expend-ship is rated by the best-scoring half-module available to receive the task. The best-scoring half-module is also the half-module with the greatest number of missiles (whether or not the remaining, and unallocated, missiles are capable of that task). By selecting the half-module with the greatest number of missiles, we maximize the remaining number of missiles that can be used for the next strike.

The half-module scoring method uses as an input a missile type from the task's  $M^3$  list. To select the half-module with the greatest number of missiles, we initially select the first missile type from the task's  $M^3$  list. Each capable half-module on the expend-

ship is given 10 points for every capable cell in that half-module. One point is given for every cell in a capable half-module in which that cell is not capable, is loaded with a missile, and does not have an assigned task. If the task requires a ready-spare missile, the best two half-module scores are summed. Each expend-ship receives a rating equal to its highest rated half-module(s). The best capable expend-ship (i.e., the ship with the highest rating) will be marked as the candidate for the task's primary, and, if applicable, ready-spare task part assignment.

If the half-module scoring method results in no capable half-modules among any of the expend-ships, the next missile type on the task's  $M^3$  list is selected and the half-module scoring method is performed again. This continues until either a capable half-module is found on an expend ship or there are no remaining missile types in the task's  $M^3$  list.

For example, consider the ship loadout in Figure 3. When scoring each half-module for a primary task part requiring a CIII missile type, Half-Module 1 receives 20 points, Half-Module 2 receives 11 points and Half-Module 3 receives 10 points. The ship's score is 20. If the task requires primary and ready-spare task parts, the ship's score is 31, the sum of the two best half-module scores for the task.

Half-Module 1	CIII	CIII	Empty	Empty
Half-Module 2	CIII	CII	Empty	Empty
Half-Module 3	CIII	Empty	Empty	Empty

**Figure 3: Half-Module Scoring.** When scoring each half-module for a primary task part requiring a CIII missile type, Half-Module 1 receives 20 points, Half-Module 2 receives 11 points and Half-Module 3 receives 10 points. The ship's score is 20. If the task requires primary and ready-spare task parts, the ship's score is 31, the sum of the two best half-module scores for the task.

If no capable firing expend-ship exists for the task, an attempt is made to allocate the task to a firing spread-ship. We want to assign missiles to the spread-ship with the largest deviation from the mean number of missiles aboard spread ships. However, by using this logic, a spread-ship with a large number of missiles but relatively few half-modules can be completely filled up with primary and ready-spare tasking before another ship is even considered for task assignment. This can result in unassigned tasks when, for example, one of two capable ships on the firing units list has been allocated tasks to capacity and there are remaining primary and back-up task part pairs to allocate.

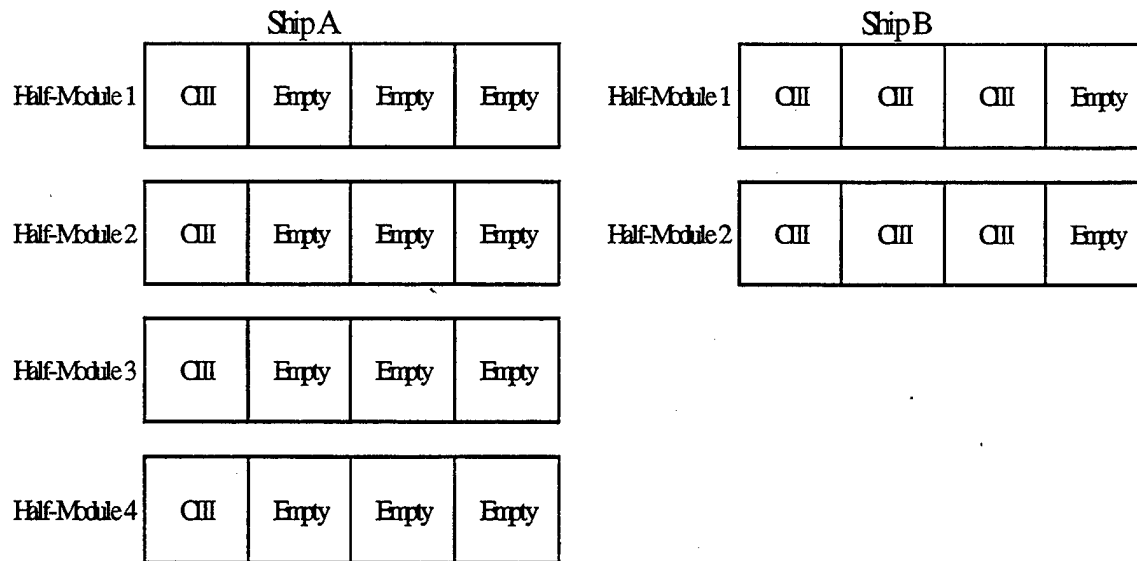
To minimize this effect, a *spread-ship scoring method* is used to select the best spread-ship by simultaneously considering the number of missiles and the number of capable half-modules for each ship. The former leads us to give one point for every non-empty cell on the ship that has not been allocated a primary task; the latter consideration is addressed by giving two points for every half-module that contains a non-empty cell that has not been allocated a primary task. The ship with the highest number of points is

viewed as the best spread-ship and is marked as the candidate for the task's primary and, if applicable, ready-spare missile assignment.

If a candidate ship is found for the primary and ready-spare task parts, and if the task requires a back-up task part, ships are considered for the assignment of the back-up task part in the same manner as they are for the assignment of the primary and ready-spare task parts. As soon as any part of the task cannot be allocated to a ship, the entire task (i.e., all parts) is marked as unassigned and the next task is considered for assignment. The allocation scheme ends when all tasks have been considered for assignment. Figure 7 illustrates the allocation scheme.

Once candidate ships have been selected for all task parts, the task parts are assigned to the respective ship's cells. Because the half-module scoring method maximizes the number of missiles available in a follow-on strike, this method is used to select the half-module for assignment (as well as to select the best expend ship to assign the task, as described directly above). Given two relevant cells, both loaded with the same type of missile, cell selection within the highest scored half-module is arbitrary between them.

For example, consider the two spread-ship loadouts in Figure 4. Ship A has four missiles, one in each of its four half-modules. Ship B has six missiles, three in each of its two half-modules. There are two ordered and conflicting tasks to assign in the same strike. Task 1 has primary, ready-spare and back-up task parts. Task 2 has primary and back-up task parts.



**Figure 4: Example Loadout.** Ship A has four missiles loaded in its four half-modules. Ship B has six missiles, three in each of its two half-modules. There are two ordered and conflicting tasks to assign, Task 1, with primary, ready-spare and back-up task parts and Task 2, with primary and back-up task parts.

If we were to make allocations based only on number of missiles, Task 1's primary and ready-spare task parts would be assigned to Ship B, while the back-up task part would be assigned to Ship A. As a result, Ship B would have five missiles remaining after the strike (assuming ready-spare and back-up task parts are not fired) and Ship A would still have four missiles. Because Task 2 conflicts with Task 1, Task 2 cannot be assigned to Ship B; this would result in a failure to place the back-up task part (see Figure 5).

Ship A					Ship B				
Half-Module 1	TI-BU	Empty	Empty	Empty	Half-Module 1	TI-PRI	CIII	CIII	Empty
Half-Module 2	CIII	Empty	Empty	Empty	Half-Module 2	TI-RS	CIII	CIII	Empty
Half-Module 3	CIII	Empty	Empty	Empty					
Half-Module 4	CIII	Empty	Empty	Empty					

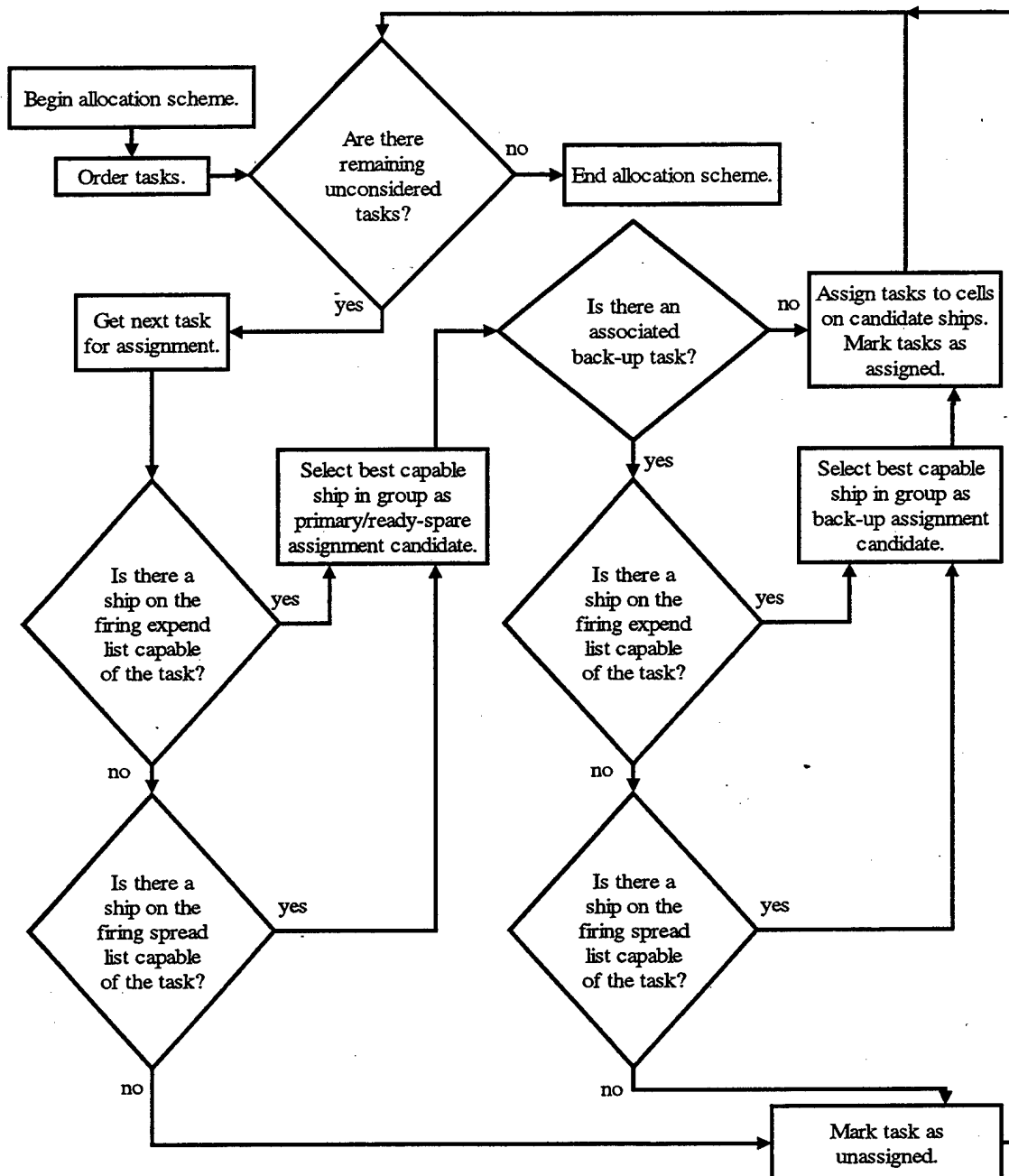
**Figure 5: Spread-Ship Allocation Based on Number of Missiles.** Assigning tasks based solely on number of missiles, we assign Task 1's primary and ready-spare parts to Ship B. Task 1's back-up part is assigned to Ship A. Task 2 cannot be assigned because there is no ship to accommodate the back-up part.

Balancing the number of missiles and capable half-modules among the two ships by using the spread-ship scoring method provides a superior outcome. Using the spread-ship scoring method to consider the number of capable half-modules as well as the number of missiles on the ship, Ship A's score of 12 over Ship B's score of 10 causes Task 1's primary and ready-spare parts to be assigned to Ship A. Task 1's back-up task part is assigned to Ship B. After the assignment of Task 1, Ship A's score is reduced to 9 and Ship B's score remains at 10. Therefore, Ship B is assigned Task 2's primary part and Ship A is assigned Task 2's back-up task part. Using this method, there are no unassigned task parts (see Figure 6).

Ship A					Ship B				
Half-Module 1	T1-PRI	Empty	Empty	Empty	Half-Module 1	T1-BU	CIII	CIII	Empty
Half-Module 2	T1-RS	Empty	Empty	Empty	Half-Module 2	T2-PRI	CIII	CIII	Empty
Half-Module 3	T2-BU	Empty	Empty	Empty					
Half-Module 4	CIII	Empty	Empty	Empty					

**Figure 6: Spread-Ship Allocation Using Spread-Ship Scoring Method.** By using the spread-ship scoring method, Ship A has a score of 12 and Ship B has a score of 10. Because Spread-ship A has the higher score, Task 1's primary and ready-spare parts are assigned to it. Task 1's back-up part is assigned to Ship B. Ship A now has its score reduced to 9 while Ship B's score remains at 10. Task 2's primary part is assigned to Ship B and the back-up part is assigned to Ship A. By using the spread-ship scoring method, we are able to assign all task parts.





**Figure 7: Task Allocation Scheme.** If possible, tasks are assigned to firing expend-ships before firing spread-ships for all task parts. The best expend-ship is determined by the half-module scoring method. The best spread-ship is determined by the spread-ship scoring method. If all task parts have candidate ships, the task parts are assigned to the respective ship's cells using the half-module scoring method. If one or more task parts does not have a candidate ship, none of the task parts is assigned.

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### **III. RESULTS**

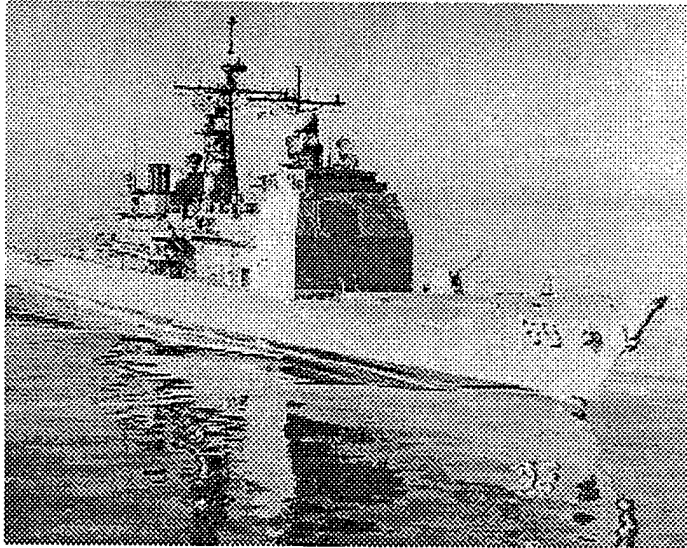
#### **A. IMPLEMENTATION**

The heuristic is implemented in Java Version 2 [Java, 1999], and is run on a 500 MHz personal computer with an Athlon processor. The heuristic's implementation uses twelve Java classes and 197 methods within its 3200 lines of code. Kirk's integer programming-based methods are implemented in GAMS Version 2.50 [GAMS, 1999] using the CPLEX solver Version 6.5 [ILOG, 1999], and run on a 333 MHz PC with a Pentium II processor.

#### **B. SCENARIO DESCRIPTIONS**

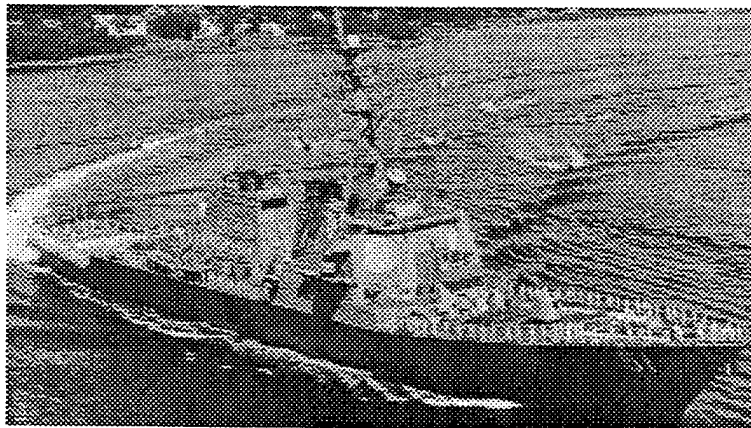
To compare the quality of the heuristic's allocations to those obtained with Kirk's two integer programming-based methods, Hierarchical Restriction and Heuristic Hierarchical Restriction, the same set of test data must be used with all models. NSWCCD developed a variety of scenarios to exercise a range of task quantities, and operator-specified preferences such as designating certain ships as ones that incur employment penalties. Six base scenarios are denoted numerically (i.e., Scenarios 1-6). In addition, there are five total variations on the base scenarios that exercise user preferences. These are labeled alpha-numerically (e.g., Scenario 5b).

Each scenario uses three different classes of land-attack-capable ships, each with a standard loadout of two TLAM variants. Ticonderoga class cruisers (Figure 8) are loaded with 16 block-II C, and 16 block-III C. One block-II C is loaded in the first cell of every odd-numbered half-module. One block-III C is loaded in the first cell of every even-numbered half-module.



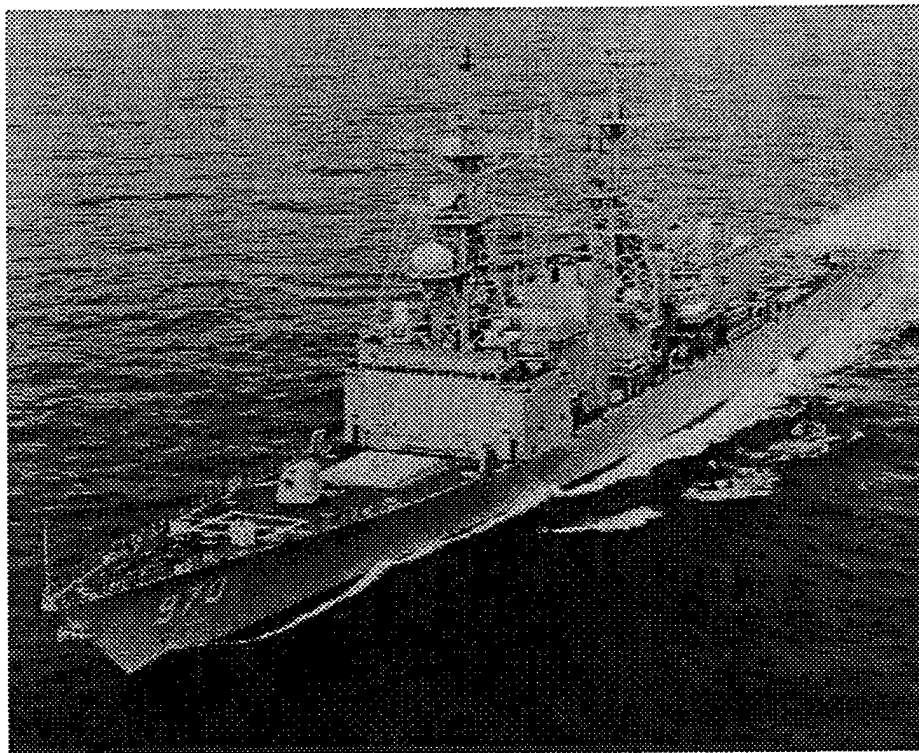
**Figure 8: USS NORMANDY (CG-60), a TICONDEROGA Class Cruiser [U.S. Navy, 1999a]. Each CG is loaded with 16 block-II C and 16 block-III C to yield a total inventory of 32 Tomahawk missiles.**

Similarly, Arleigh Burke destroyers (Figure 9) have one block-II C loaded in the first cell of every odd-numbered half-module, and a block-III C in the first cell of every even-numbered half-module, yielding a total loadout of 12 block-II C and 12 block-III C missiles.



**Figure 9: USS ARLEIGH BURKE (DDG-51), an ARLEIGH BURKE Class Destroyer [U.S. Navy, 1999b]. Each DDG is loaded with 12 block-II C and 12 block-III C to yield a total inventory of 24 Tomahawk missiles.**

Spruance class destroyers (Figure 10) are loaded with 31 block-II C and 30 block-III C TLAM. Each half-module, except the half-module containing the VLS strike-down crane, is loaded with two block-II C, and two block-III C missiles. The first two cells in every odd-numbered half-module are loaded with block-III C missiles; the last two cells are loaded with block-II C missiles. Even-numbered half-modules have an opposite configuration, i.e., block-II C missiles are loaded in the first two cells and block-III C are missiles loaded in the last two cells. The half-module that houses the strike-down crane has one block-II C missile in its only cell. Figure 11 illustrates a sample VLS loadout for a SPRUANCE class destroyer.



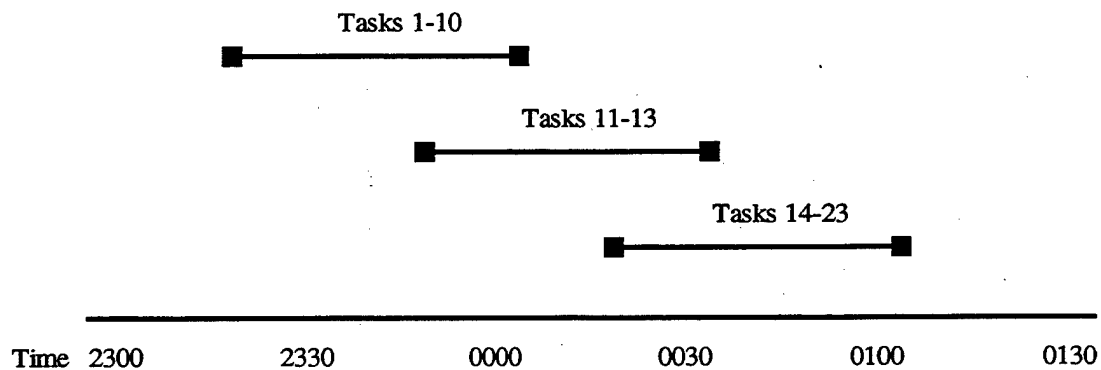
**Figure 10: USS CARON (DD-970), a SPRUANCE Class Destroyer [U.S. Navy, 1999c]. Each DD is loaded with 31 block-II C and 30 block-III C to yield a total inventory of 61 Tomahawk missiles.**

Half-Module 3	CII	CII	CIII	CIII	CII	CII	CIII	CIII	Half-Module 1
Half-Module 4	CII	CII	CIII	CIII	CII	CII	CIII	CIII	Half-Module 2
Half-Module 7	CII	CII	CIII	CIII	CII	CII	CIII	CIII	Half-Module 5
Half-Module 8	CII	CII	CIII	CIII	CII	CII	CIII	CIII	Half-Module 6
Half-Module 11	CII	CII	CIII	CIII	CII	CII	CIII	CIII	Half-Module 9
Half-Module 12	CII	CII	CIII	CIII	CII	Strike-Down Crane			Half-Module 10
Half-Module 15	CII	CII	CIII	CIII	CII	CII	CIII	CIII	Half-Module 13
Half-Module 16	CII	CII	CIII	CIII	CII	CII	CIII	CIII	Half-Module 14

**Figure 11: Sample SPRUANCE Class Destroyer Vertical Launching System (VLS) Loadout.** SPRUANCE class destroyers are loaded with 31 block-II C and 30 block-III C missiles. Each half-module, except the half-module containing the VLS strike-down crane, is loaded with two block-II C and two block-III C missiles. The first two cells in every odd-numbered half-module are loaded with block-III C missiles; the last two cells are loaded with block-II C missiles. Even-numbered half-modules have an opposite configuration, i.e., block-II C missiles are loaded in the first two cells and block-III C missiles are loaded in the last two cells. Refer to Figure 1 for the cell numbering convention.

For each scenario, a subset of 104 total tasks is used. All tasks are separated into groups of thirteen. Each group requires thirteen primary, eight ready-spare and eight back-up Tomahawk missiles. Each task in the group has overlapping preparation and launch times, preventing the assignment of any two tasks in the same group to the same half-module. In addition to a task conflicting with the others in its group, if there is a

group of tasks scheduled to be launched in the subsequent time period, the last three tasks in the group conflict with the first ten tasks in the following group. For example, consider a scenario with 23 tasks. Tasks 1-10, 11-13, and 14-23 have launch times of 0000, 0030, and 0100, respectively. Tasks 1-10 conflict with each other and with tasks 11-13. Tasks 11-13 conflict with Tasks 1-10 and with Tasks 14-23. Tasks 14-23 conflict with Tasks 11-13 but not with Tasks 1-10. Figure 12 graphically represents the conflicting groups. Horizontal lines representing each task group span the 45 minutes needed to prepare a missile in its half-module before launch.



**Figure 12: Conflicting Task Sets.** Tasks 1-10, 11-13, and 14-23 have a launch time of 0000, 0030, and 0100, respectively. Tasks 1-10 conflict with Tasks 11-13. Tasks 11-13 conflict with Tasks 1-10 and with Tasks 14-23. Tasks 14-23 conflict with Tasks 11-13. Horizontal lines representing each task group span the 45 minutes needed to prepare a missile in its half-module before launch.

Tasks may have differing  $M^3$  lists. Table 3 illustrates preferred missile types for each task for the entire data set. The columns show task groups and the order of preference for each missile type within each task group. An entry of 1 or 2 indicates that the missile types are the first or second choices, respectively, for the corresponding set of tasks. A column listing of N/A indicates that the missile type is not valid for the given

task. For example, Tasks 1-13 can use either block-II or block-III missiles, but block-II missiles are preferred. Tasks 27-39 can only use block-III missiles.

Tasks	M <sup>3</sup> List	
	Block-II	Block-III
1-13	1	2
14-26	1	2
27-39	N/A	1
40-52	N/A	1
53-65	1	2
66-78	1	2
79-91	1	2
92-104	N/A	1

**Table 3: M<sup>3</sup> List Requirements.** For example, Tasks 1-13 can be executed by block-II or block-III missiles. However, block-II missiles are preferred. Tasks 27-39 can be executed only by block-III missiles.

Table 4 summarizes scenario attributes. The first column indicates the scenario number. The following three columns give the number and type of ships eligible to be employed. Columns five through seven list the scenario's primary, ready-spare and back-up task part requirements. Columns eight and nine indicate whether or not it is desired to spread primary and back-up task parts, respectively, to as many ships as possible in the scenario. The last three columns give the number of expend-designated ships, number of launch areas and the ships with an employment penalty, respectively. Although Scenarios 5, 5A and 5B have only one launch area, some of the tasks (i.e., Tasks 66-78) can only be executed by a subset of the eligible ships. Scenario 6 incorporates tasks from Scenario 5 and fixes them in specific cells aboard eligible ships. Additional tasks must be assigned without altering the allocation of the fixed tasks. None of the scenarios uses ships with geographic penalties or ghost tasks.



Scenario	Number of Firing Platforms			Tasks Assigned			PS	BUS	Number of Expend Ships	Number of Launch Areas	Ships with an empPen
	CG	DDG	DD	PRI	RS	BU					
1	2	1	1	13	8	8	Y	N	0	1	1 CG
1A	2	1	1	13	8	8	N	N	1	1	NONE
1B	2	1	1	13	8	8	N	Y	0	1	NONE
2	2	1	1	26	16	16	N	N	0	1	1 CG
2A	2	1	1	26	16	16	Y	N	0	2	1 CG
3	2	1	1	52	32	32	Y	N	0	1	1 CG
4	2	1	1	65	40	40	Y	N	0	1	1 CG
5	3	2	2	78	48	48	Y	N	0	1	1 CG
5A	3	2	2	78	48	48	Y	N	3	1	1 CG
5B	3	2	2	78	48	48	Y	N	0	1	2 CG, 1 DD
6	3	2	2	104	64	64	Y	N	3	1	1 CG

**Table 4: Summary of Scenarios.**

**Notes:**

1. CG refers to a TICONDEROGA class cruiser. DDG is used to denote an ARLEIGH BURKE class destroyer. DD indicates a SPRUANCE class destroyer.
2. PRI, RS and BU refer to primary, ready-spare and back-up task parts respectively.
3. The "PS" column indicates user preference of spreading primary task parts among as many ships as possible.
4. The "BUS" column indicates user preference of spreading back-up task parts among as many ships as possible.
5. Scenario 1A demonstrates allocations with an expend ship.
6. Scenario 1B demonstrates the user preference of spreading back-up task parts among as many ships as possible.
7. Scenario 2A has two geographically distinct launch areas. The first launch area has a CG and a DD eligible for tasking. The second launch area has a CG and DDG eligible for tasking.
8. Scenarios 5, 5A and 5B have 13 tasks that can only be executed by a subset of the eligible ships. This illustrates the effect of launch area obstructions for some ships or incomplete mission data preventing execution of all tasks. These scenarios also demonstrate allocations to firing expend ships and ships with employment penalties while assigning larger numbers of tasks.

### C. RESULTS

Each scenario is scored with respect to eight objectives, which are given in decreasing order of priority. Objective 1 sums all unassigned task parts; this term should be as small as possible. Objective 2 gives the total number of ships with an employment penalty used to meet tasking requirements. Spread-ships without employment penalties should be used as long as there are no unassigned task parts. Objective 3 calculates the number of primary task parts assigned to expend-ships. The number of tasks assigned to expend-ships should be as large as possible. Objective 4 sums all spread-ship deviations from the mean number of missiles on all employed spread ships. This sum is calculated by determining the average remaining inventory among spread-ships after the strike (assuming that ready-spares and back-up missiles will not be fired) and summing the difference from the mean for each ship. Lower values for Objective 4 indicate a more even spread of missiles after the strike. Objective 5 calculates the number of ships that have primary missiles assigned to them. The resulting value includes only ships in launch areas where we want to spread primary missiles to as many ships as possible. Objective 6 determines the number of ships that have back-up missiles assigned to them for launch areas where we prefer to spread back-up missiles to as many ships as possible. If the spread option is selected for either primary or back-up missiles, the resulting value (for Objective 5 or Objective 6, respectively) should be as high as possible. Objective 7 sums the  $M^3$  list positions for all primary, ready-spares, and back-up missiles. The least capable missiles (i.e., the missiles with the lowest  $M^3$  positions) should be used to yield a value as low as possible for Objective 7. Objective 8 calculates the maximum follow-on

salvo size for all ships participating in the scenario. The maximum follow-on salvo size should be as large as possible.

Table 5 summarizes scenario results for each objective. Solutions obtained with our heuristic method are tabulated in addition to those obtained with Kirk's Hierarchical Restriction (HR) and Heuristic Hierarchical Restriction (HHR) methods. We also give associated solution times for all three methods. A column entry of N/A indicates that an operator-selected option, such as primary missile spreading in a launch area, is not used in the scenario.

SCENARIO	Objective								Solution Time (Seconds)
	1	2	3	4	5	6	7 PRI/RS/BU	8	
1HR(Kirk)	0	0	N/A	34	3	N/A	13 / 8 / 8	160	26
1HHR(Kirk)	0	0	N/A	34	3	N/A	13 / 8 / 8	159	8
1Heuristic	0	0	N/A	40	2	N/A	13 / 8 / 8	172	2
1AHR(Kirk)	0	N/A	10	8.67	N/A	N/A	13 / 8 / 8	160	34
1AHR(Kirk)	0	N/A	10	8.67	N/A	N/A	13 / 8 / 8	159	15
1AHeuristic	0	N/A	9	8	N/A	N/A	13 / 8 / 8	173	2
1BHR(Kirk)	0	N/A	10	8.67	N/A	4	13 / 8 / 8	160	36
1BHR(Kirk)	0	N/A	10	8.67	N/A	2	13 / 8 / 8	159	12
1BHeuristic	0	N/A	9	8	N/A	1	13 / 8 / 8	173	2
2HR(Kirk)	0	0	N/A	23	3	N/A	26 / 16 / 16	157	336
2HHR(Kirk)	0	0	N/A	23	3	N/A	26 / 16 / 16	156	114
2Heuristic	0	0	N/A	32	3	N/A	31 / 18 / 19	158	3
2AHR(Kirk)	0	1	N/A	42.5	2	N/A	26 / 20 / 16	146	103
2AHR(Kirk)	0	1	N/A	42.5	2	N/A	26 / 19 / 19	146	22
2AHeuristic	0	1	N/A	44.5	2	N/A	29 / 16 / 16	156	8
3HR(Kirk)	0	0	N/A	15.5	3	N/A	52 / 32 / 32	137	1625
3HHR(Kirk)	0	0	N/A	15.5	3	N/A	52 / 32 / 32	129	1176
3Heuristic	0	1	N/A	15	4	N/A	52 / 32 / 32	133	22
4HR(Kirk)	0	1	N/A	0	4	N/A	65 / 52 / 40	127	6133
4HHR(Kirk)	0	1	N/A	0	4	N/A	65 / 52 / 48	120	3983
4Heuristic	0	1	N/A	30	4	N/A	76 / 41 / 40	110	40
5HR(Kirk)	0	0	N/A	11.4	4	N/A	78 / 50 / 48	268	10976
5HHR(Kirk)	0	0	N/A	11.4	4	N/A	78 / 50 / 48	258	2449
5Heuristic	0	0	N/A	46.4	6	N/A	89 / 54 / 52	253	36
5AHR(Kirk)	0	0	65	34	6	N/A	78 / 52 / 48	242	7356
5AHR(Kirk)	0	0	65	34	5	N/A	78 / 52 / 48	229	1800
5AHeuristic	0	0	44	25	6	N/A	83 / 52 / 48	250	36
5BHR(Kirk)	0	1	N/A	21.4	4	N/A	78 / 62 / 48	268	34340
5BHR(Kirk)	0	1	N/A	21.4	4	N/A	78 / 62 / 48	260	6488
5BHeuristic	0	1	N/A	38.8	5	N/A	90 / 53 / 55	251	87
6HR(Kirk)	0	0	69	24	6	N/A	124 / 84 / 80	209	261
6HHR(Kirk)	0	0	69	24	6	N/A	126 / 84 / 78	204	98
6Heuristic	0	0	66	35	6	N/A	128 / 82 / 80	219	56

**Table 5: Summary of Scenario Results.** This table compares our heuristic's performance to Kirk's two integer programming-based methods with respect to the eight objectives and solution times. An entry marked with N/A indicates that the user-specified preference was not selected for that scenario. HR and HHR times are obtained with a 333 MHz personal computer, and the heuristic times are obtained with a 500 MHz personal computer.

Table 6 summarizes the percentage deviation between our heuristic and Kirk's two integer programming-based methods as a ratio of the relevant value obtained with

our heuristic and the respective value obtained with the integer programming-based method, multiplied by 100%. A column entry of N/A indicates that an operator-selected option, such as primary missile spreading in a launch area, is not used in the scenario.

SCENARIO	Objective Percentage Deviation								Solution Time
	1	2	3	4	5	6	7 PR/RS/BU	8	
1HR	100%	100%	N/A	118%	66%	N/A	100% / 100% / 100%	107%	6%
1HR	100%	100%	N/A	118%	66%	N/A	100% / 100% / 100%	107%	19%
1AHR	100%	N/A	90%	92%	N/A	N/A	100% / 100% / 100%	108%	4%
1AHR	100%	N/A	90%	92%	N/A	N/A	100% / 100% / 100%	109%	10%
1BHR	100%	N/A	90%	92%	N/A	25%	100% / 100% / 100%	108%	4%
1BHR	100%	N/A	90%	92%	N/A	50%	100% / 100% / 100%	109%	13%
2HR	100%	100%	N/A	139%	100%	N/A	119% / 113% / 118%	101%	1%
2HR	100%	100%	N/A	139%	100%	N/A	119% / 113% / 118%	101%	3%
2AHR	100%	100%	N/A	105%	100%	N/A	107% / 85% / 100%	108%	8%
2AHR	100%	100%	N/A	105%	100%	N/A	107% / 89% / 119%	108%	36%
3HR	100%*	*	N/A	97%	133%	N/A	100% / 100% / 100%	97%	1%
3HR	100%*	*	N/A	97%	133%	N/A	100% / 100% / 100%	103%	2%
4HR	100%	100%	N/A	**	100%	N/A	115% / 79% / 103%	87%	1%
4HR	100%	100%	N/A	**	100%	N/A	115% / 79% / 85%	93%	1%
5HR	100%	100%	N/A	407%	150%	N/A	114% / 108% / 92%	94%	1%
5HR	100%	100%	N/A	407%	150%	N/A	114% / 108% / 92%	98%	2%
5AHR	100%	100%	68%	74%	100%	N/A	106% / 100% / 100%	103%	1%
5AHR	100%	100%	68%	74%	120%	N/A	106% / 100% / 100%	109%	2%
5BHR	100%	100%	N/A	181%	120%	N/A	115% / 85% / 87%	94%	1%
5BHR	100%	100%	N/A	181%	120%	N/A	115% / 85% / 87%	97%	1%
6HR	100%	100%	96%	146%	100%	N/A	103% / 98% / 96%	105%	21%
6HR	100%	100%	96%	146%	100%	N/A	102% / 97% / 100%	107%	57%

**Table 6: Summary of Percentage Deviations Between the Heuristic and the Integer Programming-Based Solutions.** Percentage deviation between our heuristic and Kirk's two integer programming-based methods is calculated as a ratio of the relevant value obtained with our heuristic and the respective value obtained with the integer programming-based method, multiplied by 100%. A column entry of N/A indicates that an operator-selected option, such as primary missile spreading in a launch area, is not used in the scenario. \* In Scenario 3, all tasks can only be assigned with the additional use of a ship with an employment penalty. Without this ship, three tasks possessing only primary task parts cannot be assigned. \*\* In Scenario 4, Kirk assigns primary task parts to all spread ships such that they have the same number of missiles at the end of the strike (i.e., an Objective 4 value of zero) whereas we have a deviation from the mean number of missiles of 30.

In general, our heuristic provides acceptable solutions for most objectives in a fraction of the time required by Kirk's integer programming-based methods. Most importantly, all tasks can be assigned in each scenario. In every scenario, except Scenario 3, our heuristic is able to select the same set of ships as Kirk's methods. In Scenario 3, all tasks can only be assigned with the additional use of a ship with an employment penalty. Without this ship, three tasks possessing only primary task parts cannot be assigned. Because minimizing the number of unassigned parts has a higher priority than using a ship with an employment penalty, the latter option is exercised.

Our heuristic does not produce consistently good results for Objective 3, assigning as many tasks as possible to expend-ships. In Scenarios 1A, 1B, and 6, the number of primary tasks we assign to expend-ships relative to the number of tasks Kirk assigns to expend-ships is 90%, 90% and 96% respectively. However, in Scenario 5A, the number of primary tasks assigned to expend ships is only 68% of the number of tasks Kirk assigns with both of his methods. In Scenario 5A, all available cells on expend-ships are filled not only with primary task parts, but also with ready-spare and back-up task parts because of the preference given to assigning any task part to an expend-ship rather than to a spread-ship. Although there is no specific objective that benefits from the assignment of back-up task parts to expend-ships, one may argue that these assignments should be preferred in an operational setting where back-up task parts are used.

Our heuristic also gives inconsistent results for Objective 4, sum of spread-ship deviations from the mean. With the exception of Scenario 4, our heuristic can be as low

as 74% of Kirk's integer programming methods or as high as 407%. In Scenario 4, Kirk assigns primary task parts to all spread ships such that they have the same number of missiles at the end of the strike (i.e., an Objective 4 value of zero). Our heuristic does not perform as well in Scenario 4 because the spread-ship scoring method seeks to maintain feasible allocations with respect to primary and back-up task parts by balancing the number of available half-modules and the number of missiles between spread-ships, rather than directly making assignments to the spread-ship with the largest deviation from the mean.

Our heuristic performs very well for Objective 5, spreading primary tasks to as many ships as possible. In every scenario, with the exception of Scenario 1, our heuristic spreads primary task parts to at least as many ships as Kirk's two methods. In Scenario 1, Kirk uses three ships to make all assignments. Because the data set is small, and the spread-ship scoring method prefers assigning tasks to the CG and DD over the DDG, our heuristic is able to divide the entire set of tasks between two ships. In Scenarios 3, 5, and 5B we are able to exceed Kirk's values for Objective 5 obtained with Heuristic Hierarchical Restriction by 33%, 50%, and 20%, respectively. Our heuristic always allows assignment to any spread-ships without employment penalties whereas Kirk's integer programming-based methods may only consider a subset of spread-ships if tasking can be met without using all spread-ships.

Scenario 1B is the only data set for which Objective 6, spreading back-up missiles, is relevant. In this scenario, there are eight back-up task parts that must be allocated to four ships. Again, the number of tasks is so small that two ships are able to

accommodate all tasks. Our heuristic's spread-ship scoring method assigns every back-up task to the same ship whereas Kirk's Hierarchical Restriction and Heuristic Hierarchical Restriction methods spread back-up task parts to four and two ships, respectively. Our heuristic has no specific method for spreading primary or back-up task parts. We expect that the spread-ship scoring method, in balancing the number of half-modules and number of missiles between spread-ships, will allocate the task parts more evenly among ships for scenarios with larger task sets that will necessitate the use of the majority of the eligible ships.

Our heuristic results for Objective 7, sum of  $M^3$  positions, are excellent for all scenarios. Our heuristic is able to achieve from 79%-119% of values obtained with either of Kirk's two methods because we always seek to assign tasks to the missile type lowest on the  $M^3$  list.

Results are also excellent for Objective 8, maximum follow-on salvo. Because the half-module scoring method seeks to maximize the number of missiles that can be used in the next strike, we are able to obtain maximum follow-on salvo values from 87%-109% of either of Kirk's two methods.

Our heuristic's run time is faster than Kirk's integer programming-based models, even when we consider his 333 MHz personal computer versus our 500 MHz personal computer. The difference in solution times is significant for the larger, more difficult, problems. In Scenarios 3 through 5B, the time savings is between 27 minutes and 9.5 hours. Because many tasks are already fixed in Scenario 6, solution times for our



heuristic and Kirk's integer programming-based models are faster than the other scenarios with an equally large number of tasks (i.e., Scenario 5, 5A, and 5B).

Our heuristic is fast enough to be implemented in an operational setting. In addition, the heuristic is simpler to describe, understand, modify, test, and tune than formal integer programming-based methods. Substituting a more efficient computational language than Java can improve the heuristic's solution times. By contrast, Kirk's integer programming-based methods are implemented using specially tuned, state-of-the-art software, and already exhibit the best performance currently achievable. It is not clear how to improve the integer programming performance further, or how to certify that the result can be trusted to work reliably for all operational scenarios.

Although our heuristic is fast enough for operational use, Kirk contributed the proof we need to trust it. Without Kirk's pioneering optimization results, we would have no objective assessment of the quality of our heuristic assignments, and would thus be uncertain about recommending it to the fleet.

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## IV. CONCLUSIONS AND EXTENSIONS

### A. GENERAL

Our heuristic produces good allocations in a fraction of the time required for Kirk's integer programming-based methods. In fact, Tomahawk Strike Coordinators could use our heuristic in an operational setting to meet NCA planning requirements. However, these faster solution times sacrifice some solution quality. Allocation of as many missiles as possible to expend-ships (Objective 3) and level distribution among spread-ships (Objective 4) for some scenarios falls short of integer-programming-based methods. However, the quality of solutions for all other objectives is very close to Kirk's integer programming-based methods.

Scoring of the heuristic showed poor results for Objectives 3 and 4. In Objective 3, our preference for assigning back-up task parts to expend-ships over spread-ships reduces the number of cells available for primary task part assignment. Modifying the heuristic to deter the assignment of back-up task parts to expend-ships would improve Objective 3 scores. Specifically, we could consider using the half-module scoring method to find the best ship among *all* the ships on the firing units list (including spread-ships) for back-up task part assignment.

Selecting spread-ships with the spread-ship scoring method is useful in preventing a single ship with a relatively larger loadout but fewer half-modules from being over-assigned. However, the spread-ship scoring method does not do an adequate job of

ensuring that spread-ships have a nearly equal number of missiles after the strike (Objective 4).

We suggest the following additional modifications: The solution times obtained with the heuristic are fast enough that a more refined myopic exchange heuristic could be added to improve our initial recommendation. Moreover, although the heuristic is able to allocate all tasks to ships in the scenarios provided by NSW CDD, more scenarios should be examined to evaluate the robustness of the heuristic. For the scenarios tested, the current method of ordering tasks produces better objective values than any other ordering. However, it is possible that the heuristic may perform poorly or even fail with other data sets. Because we have no back-tracking procedure, our heuristic solutions are myopic and may possibly suffer from "cul-de-sac" failures. This is possible, but unlikely in practice and fairly straight forward to address via operator interaction and embellishments of the heuristic. An operator-specified ordering method (other than the one discussed in Section 2C) could elevate objective scores obtained for alternate scenarios. For example, in a set of tasks that are geo-feasible for all ships on the firing-units list and have the same  $M^3$  lists, ordering of tasks first by number of conflicts may be preferred. Similarly, with a task set in which some tasks can only be allocated to a very small set of missiles, task ordering by missile rarity first may be the only way to avoid unassigned task parts.

A preferred ordering by tasks parts should also be examined. In our heuristic, we arbitrarily order primary and back-up task parts before primary and ready-spare task

parts. Either a general ordering should be determined by testing a large number of tasks, or an operator-specified ordering should be allowed.

## **B. RECOMMENDATIONS**

NSWCDD developed the prioritization of the objectives used to measure the quality of solutions. Objective priority determines which ships are selected and the amount of tasking assigned to each. Fleet experience indicates that priorities may differ, depending on the Tomahawk Strike Coordinator. Although minimizing unassigned task parts (Objective 1), is unequivocally the highest priority, the prioritization of subsequent objectives is less well-defined. Our results may appeal to some TSCs more than others. For example, some TSCs may grant maximizing residual salvo-size higher importance than it currently receives. We recommend that a fleet-wide standard be adopted in order to assist in the development of tools, such as our heuristic, yielding a set of priorities common to all TSCs.

## **C. EXTENSIONS**

Although not specifically exercised, our heuristic is capable of incorporating all future VLS-based land-attack weapons. The next generation of land-attack missiles will include Tactical Tomahawk and the Land-Attack Standard Missile (LASM). Tactical Tomahawk will be unable to execute tasks designed for Tomahawk [Fennemore, 1999b]. LASM will be unique from Tomahawk of any generation and will not be able to carry out tasks other than those specifically designed for LASM [Fennemore, 1999b].

As described earlier, conflicting tasks are determined by missile type, preparation and launch times. Two Tomahawks with overlapping preparation times cannot be

allocated to the same half-module. Future missile systems, such as LASM, may not suffer from this limitation but instead would allow for simultaneous preparation of both LASM and Tomahawk missiles within the same half-module [Fennemore, 1999b]. Our heuristic is able to accommodate LASM, Tactical Tomahawk, and all other future VLS-missile weapons by appropriately modifying conflicting task set data to represent the proper compatibilities with respect to task-to-missile assignment. Similarly,  $M^3$  lists can be added as required for all future weapon types.

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